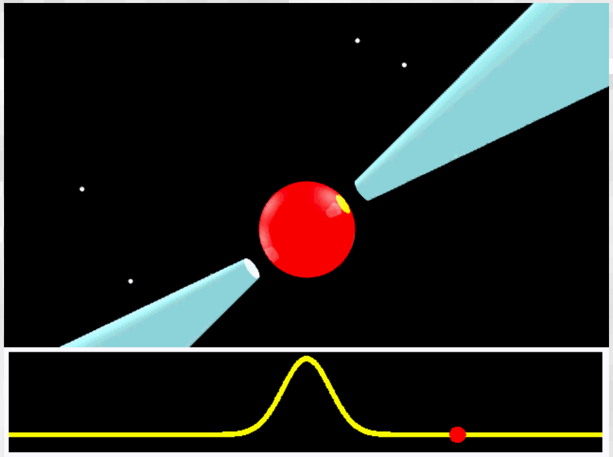
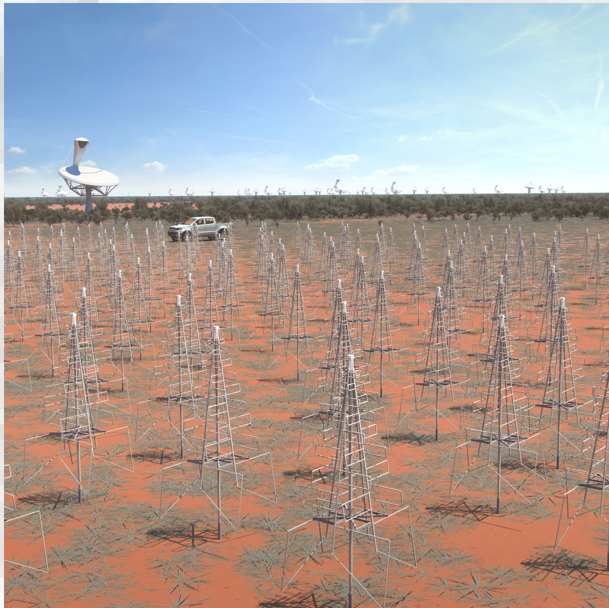
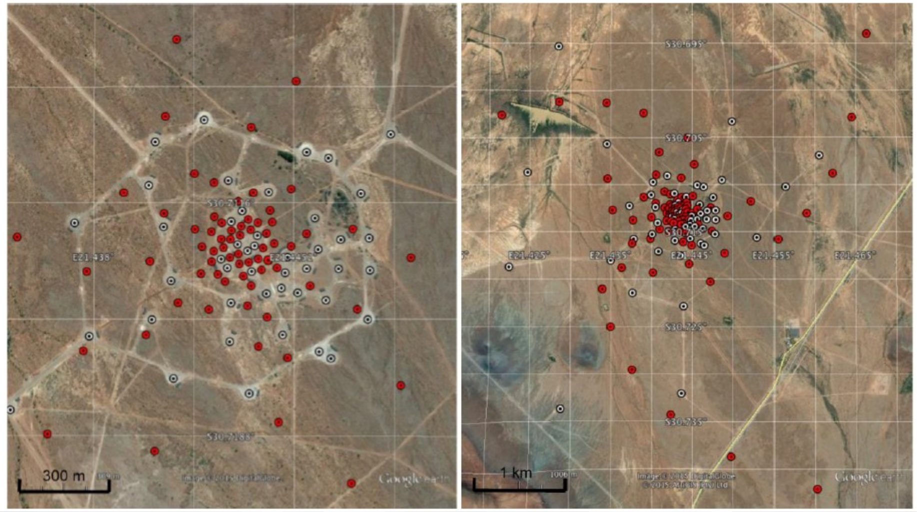
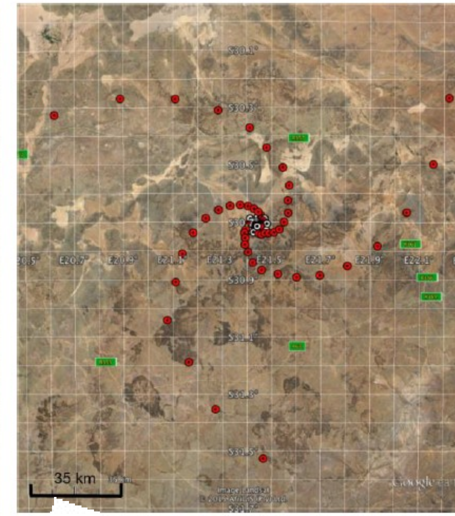
Studying Gravity with the Square Kilometre Array

Gilles Theureau
for the pulsar SKA Science Working Group

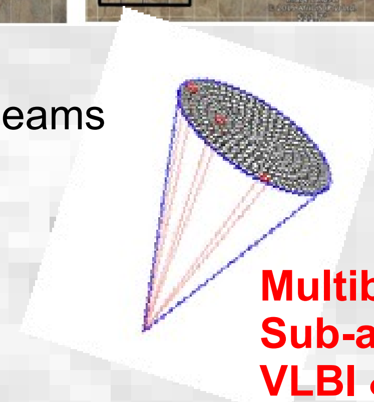






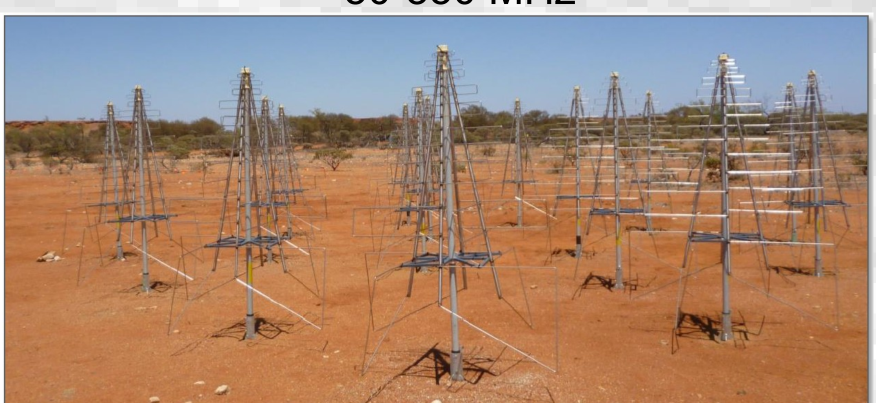


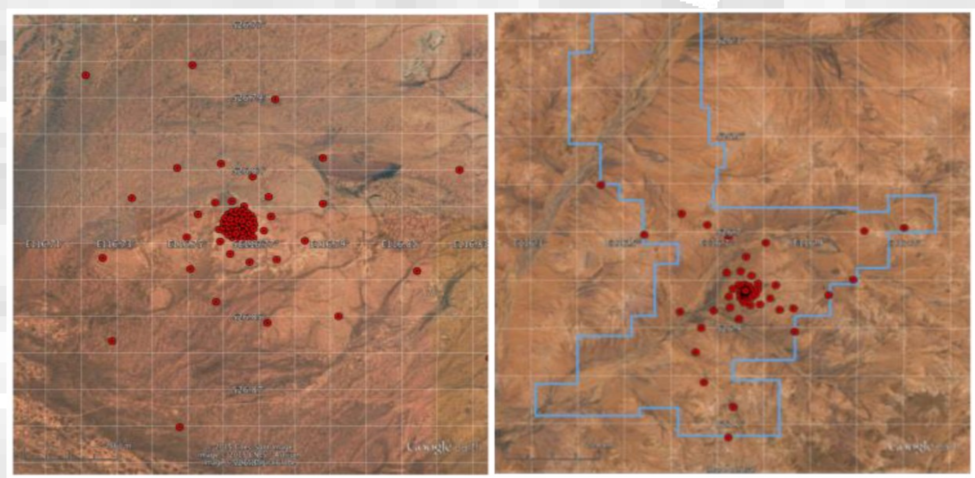
SKA1_MID: **South Africa** and surrounding countries
200 dishes (single feed) including MeerKAT, 1500 beams
0.35-1.05 GHz / 0.95-1.76 GHz / 4.6-13.8 GHz
+ 36 ASKAP dishes (focal plane arrays) in Australia



Multibeaming
Sub-arraying
VLBI & imaging

SKA1_LOW: **West Australia**
131,000 apperture array antennas , 500 beams
grouped in 512 stations
50-350 MHz



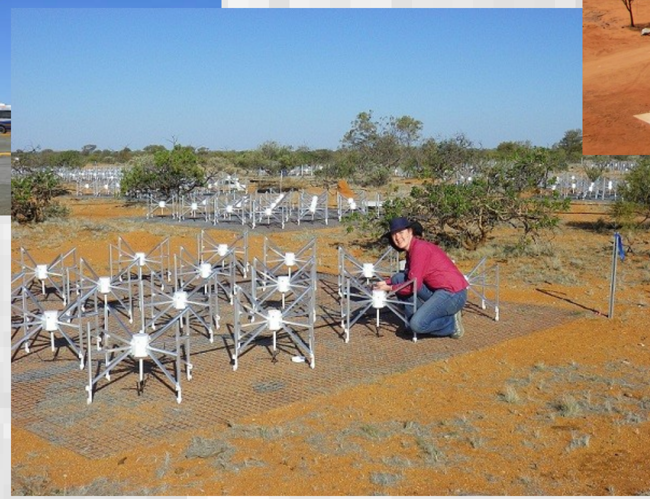


Precursors

MeerKAT (South Africa)

ASKAP (Australia)

MWA (Australia)

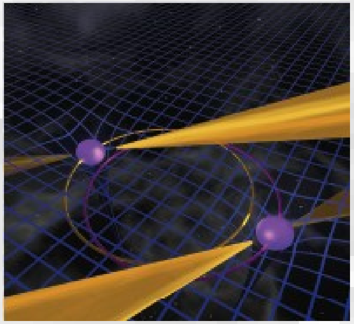
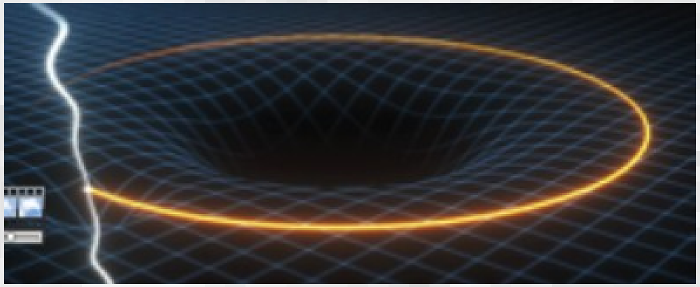
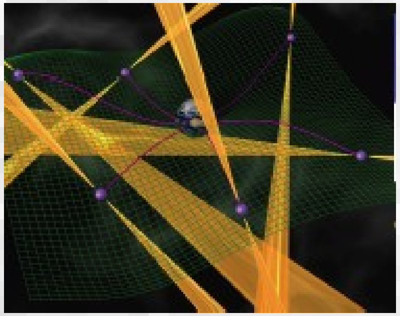
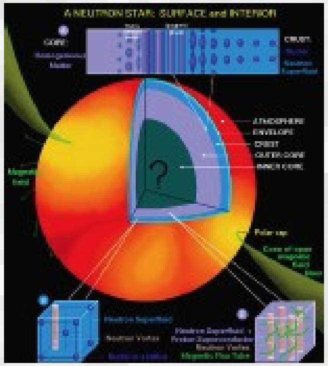


LOFAR (Netherlands)

and Pathfinders

LWA (USA)

NenuFAR (France)

SKA Pulsar Science top priorities :
(from last science working group meeting in Stokholm, August 2015)

« Understanding gravity and Fundamental interactions using pulsars and black holes »

P0 - Tripling the currently known pulsar population

P1 – Finding highly relativistic systems and improving tests of gravity in the strong field regime by at least one order of magnitude

P2 – Finding at least one pulsar – black hole binary and informing quantum gravity

P3 – detecting gravitational waves at nanoHertz frequencies

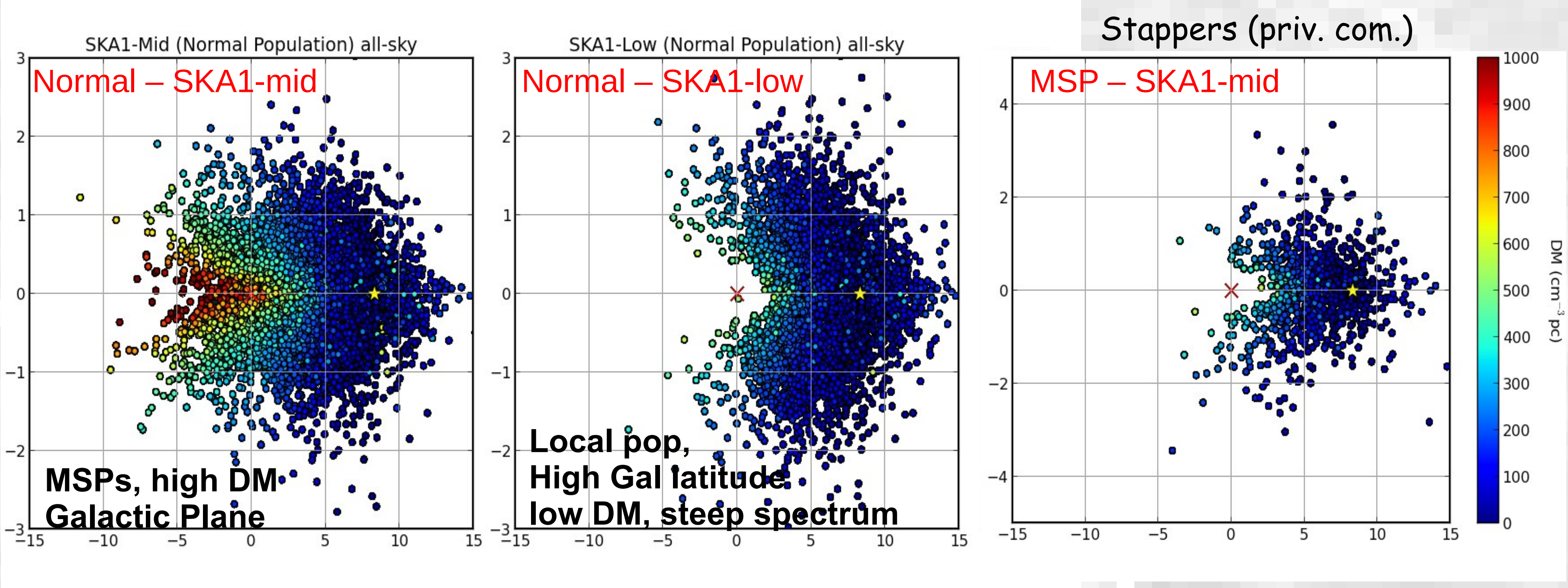
P4 – Improving the mass-radius relation (NS equation of state) by more than one order of magnitude

SKA1 will already be an excellent search machine

We can find nearly 50% of all pulsars in combination of SKA-low and SKA-mid

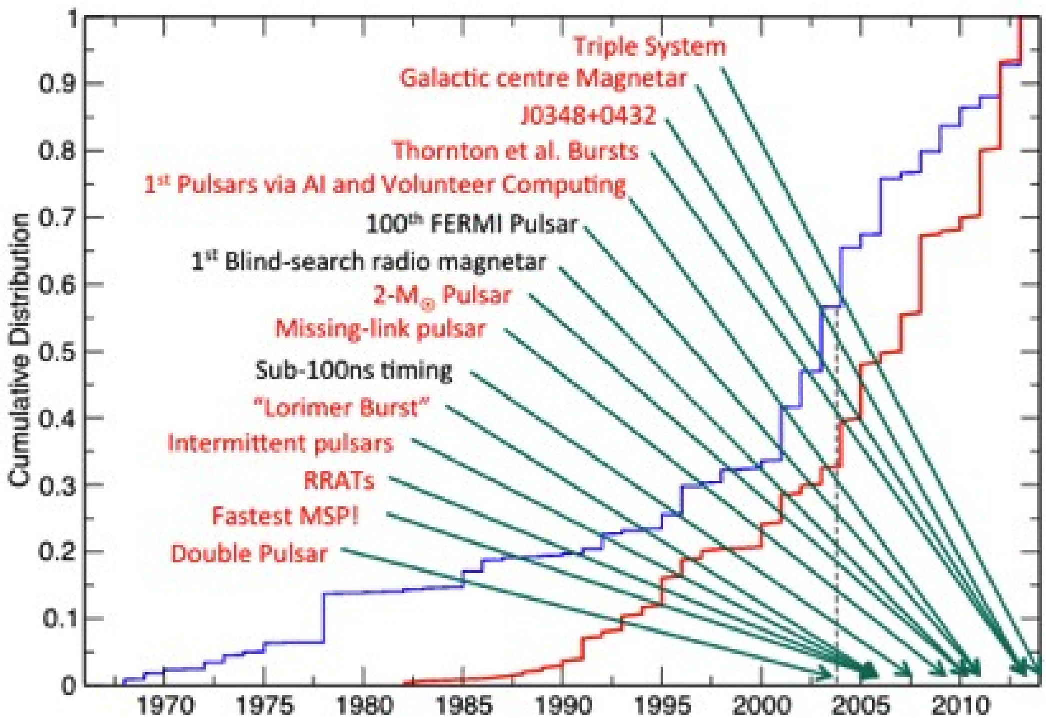
+ pilot all sky surveys already with LOFAR and soon with MeerKAT (+GBT, Parkes, etc...)

expect 9000 normal and 1500 MSPs



Characterising the pulsar population
Finding millisecond pulsars in Globular Clusters and external galaxies
Finding pulsars near to the Galactic Centre
P0 Obtaining pulsar astrometric measurements to improve GR tests
Mapping the pulsar beam
Understanding pulsars and their environments through their interactions
Mapping the Galactic structure

Among those 10,000 pulsars there should be a few gems

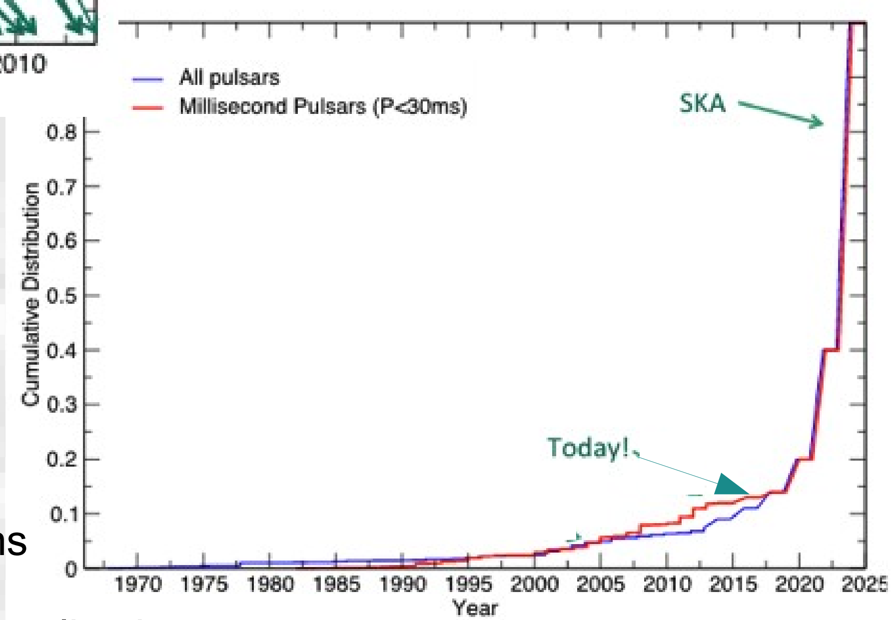


Courtesy of M.Kramer

~2500 pulsars known to date

Each blind survey has brought its bunch of special discoveries and exotic systems

Targeted search toward Fermi-LAT unassociated sources has doubled the number of known MSPs in the Galactic Plane



What's missing ?

still a pulsar-BH system
MSP next to the Galactic Centre
MSP close to the centre of a globular cluster
New highly excentric and relativistic binaries
A set of wide, low excentric orbit NS-WD systems
A triple system with an external NS
New very stable (<100 ns rms) pulsars for PTA applications

Pulsar timing in the SKA era

- **Radiometer noise:** timing precision grows with S/N
  → SKA1 >10 times more sensitive
  than current 100-m class radio telescopes

- **Pulse jitter:** limits the ultimate timing precision
  at short timescales
  → requires minimum integration time
  → SKA1 sub-arraying

- **Spin (Timing) noise:** long-term pulsar-intrinsic irregularities ; unpredictable
  (small bodies in orbit, series of micro-glitches, magnetospheric changes)
  → SKA1 will discover new very stable rotators

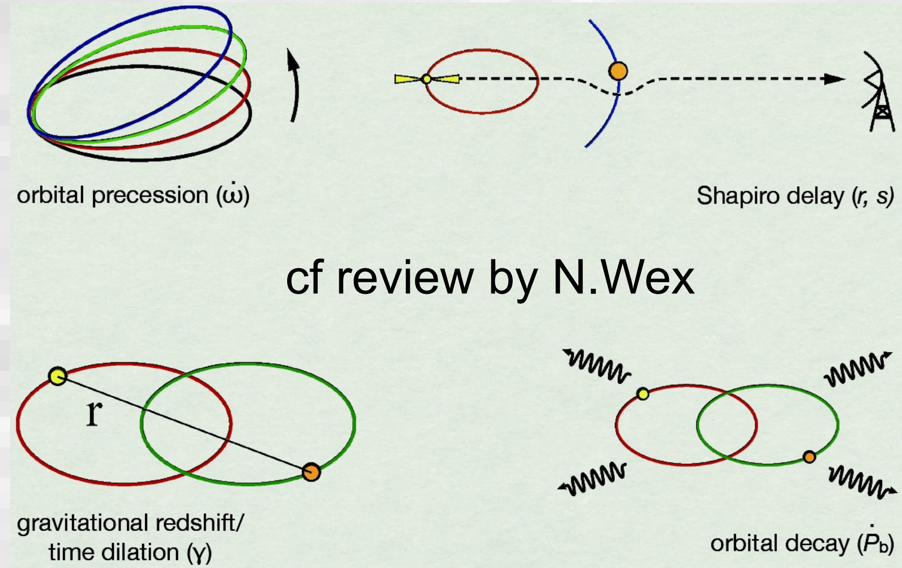
- **Interstellar medium effects :**
  Dispersive delays:
  - need multiple observing freqs (SKA1-mid)
  - need low freqs (SKA1-low)

- Scattering: requires higher (>2-3 GHz observing freqs)
  → missing SKA1_MID band 3 (1.65-3.05 GHz) for PTA applications
  → SKA1_MID band 5 (4.6-13.8 GHz) for search & timing towards Gal Centre

Why we need SKA instantaneous sensitivity

Binary pulsars used to test the quasi-stationary strong-field regime and GW damping in the framework of parametrized post-keplerian formalism (PPK : Damour&Taylor 1992)

ω	Longitude of periastron
$\dot{\omega}$	Advance of periastron
P_b	Orbital period
$\dot{P}_b$	Orbital period derivative
γ	Gravitational redshift
e	Eccentricity
r	Range of Shapiro delay
s	Shape of Shapiro delay
i	Angle of Inclination
x	Projected semi-major axis
m_A	Pulsar mass (measured in units of $M_\odot$)
m_B	Companion mass (measured in units of $M_\odot$)
M	Total mass ($M = m_1 + m_2$)



(GR)

$$\begin{aligned}
\dot{\omega} &= 3\left(\frac{P_b}{2\pi}\right)^{-5/3} G^{2/3} M^{2/3} (1-e^2)^{-1}, \\
\gamma &= e\left(\frac{P_b}{2\pi}\right)^{1/3} G^{2/3} M^{-1/3} m_B \left(1+\frac{m_2}{M}\right), \\
\dot{P}_b &= -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3} m_A m_B G^{5/3} M^{-1/3} \left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2}, \\
s &= x\left(\frac{P_b}{2\pi}\right)^{-2/3} G^{-1/3} M^{2/3} m_B^{-1}, \\
r &= G m_B.
\end{aligned}$$

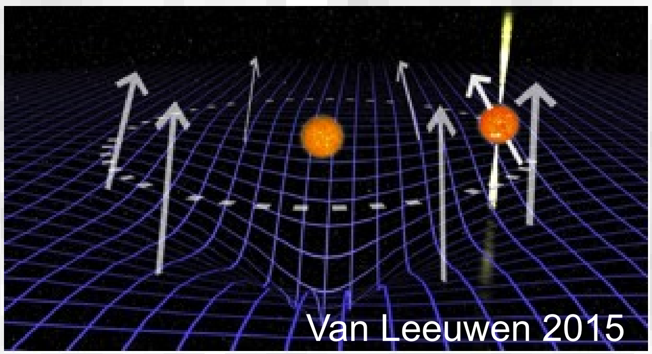
State of the art :
1^{st} order PN approximation

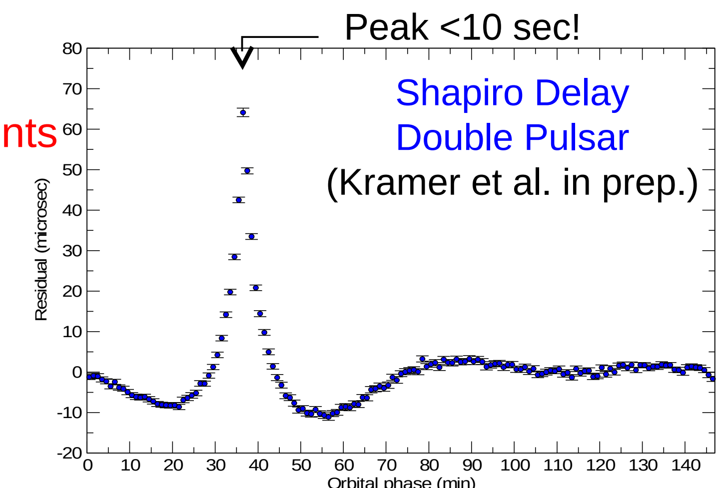
SKA will allow to measure higher order effects

Why we need SKA instantaneous sensitivity

→ discover > 100 NS-NS systems,
→ phase resolve short period orbits, particularly at conjunctions (Shapiro, eclipses)

New accurate NS masses,
New geodetic precession measurements





$m_A = 1.338148 \pm 0.000008\ M_\odot$

$m_B = 1.248915 \pm 0.000008\ M_\odot$

At 50 ns precision, Shapiro detectable at inclinations down to ~40°

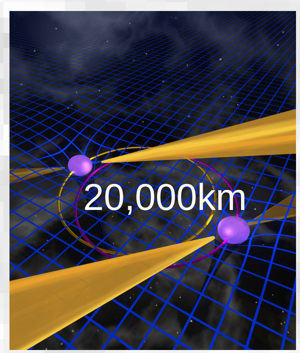
→ SKA1 will bring 5x more NS masse measurements

Get frame draging from direct $\dot{x}$ measurement
(tight binaries, large spin/orbit angle)

+ Measure Lens-Thirring

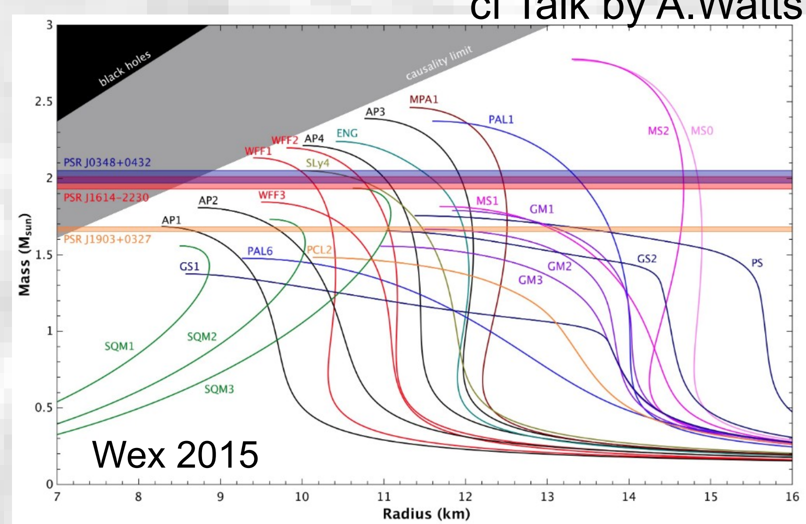
through its contribution to $\dot{\omega}$

(from accurate s , $\dot{P}_b$ and VLBI distance)



→ estimate pulsar moment of inertia
→ new constraints on EoS

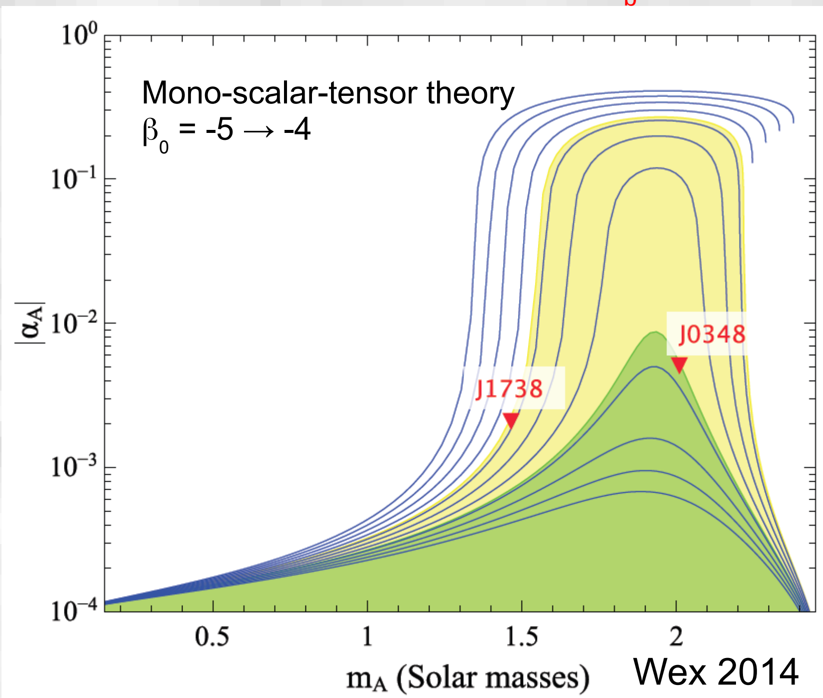
cf Talk by A.Watts

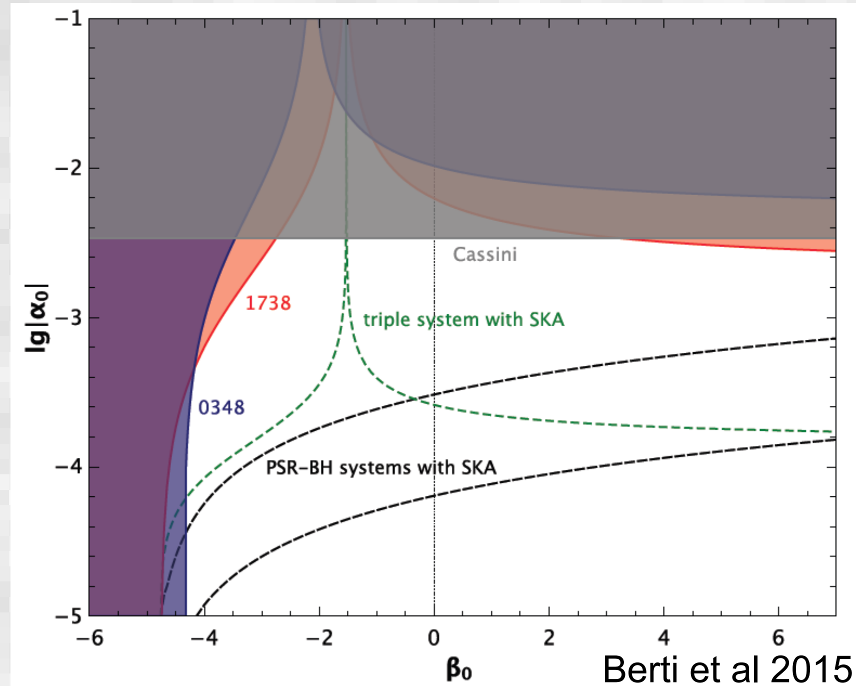


Why we need SKA instantaneous sensitivity

→ discover new highly assymetrical NS-WD systems (like J1738+0333, J0348+0432)

Test effacement property (SEP) : $\dot{P}_b$(dipolar) $\propto (\alpha_{NS} - \alpha_{WD}) \neq 0$? (α eff. coupling strength body/dipole moment)





→ new NS-WD systems in wide orbits and with small excentricities

Constrain the differential free fall rate in the MW gravitational potential (SEP-Schäfer test)

→ improve triple system J0337+1715 timing, discover a triple system with external NS

Test universality of free fall in strong external field (SEP)

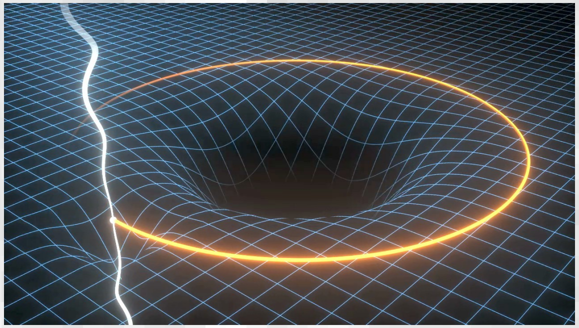
→ measure profile change or secular variation of semi-major axis ($\dot{x}$) ► Test Local Lorentz invariance (LLI) & local position invariance (LPI) of gravity

Test prefered frame effect from precession of solitary pulsars

Test prefered frame effect from precession of orbital angular momentum

Why we need SKA instantaneous sensitivity

→ optimize acceleration search and find highly relativistic binaries (NS-BH systems)



probe the spacetime around a stellar black hole

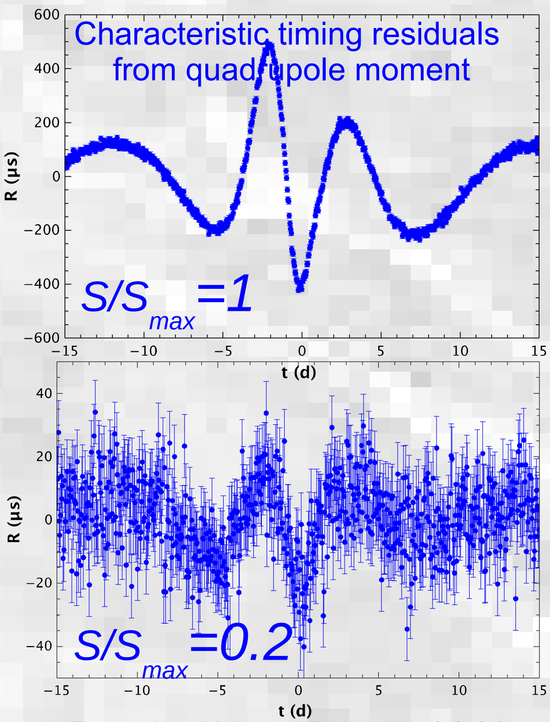
With a fast millisecond pulsar about a 10-30 $M_\odot$ BH, the SKA could measure the quadrupole ►

BH mass with precision < 0.1%

BH spin with precision < 1%

Test cosmic censorship conjecture
(∃ a maximum spin $S < GM^2/c$)

+ better test on Shapiro and GW damping



Psaltis, Wex, Kramer 2016

test the no-hair theorem to about 1% precision with a pulsar in a 0.1 yr orbit around Sgr A* (4 $10^6 M_\odot$)

No-hair theorem (BH fully defined by mass and spin)
⇒ quadrupole moment satifies $Q = -S^2/Mc^2$

- *Secular precession* caused by quadrupole is 2 orders of magnitude below frame dragging, and is not separable from frame-dragging

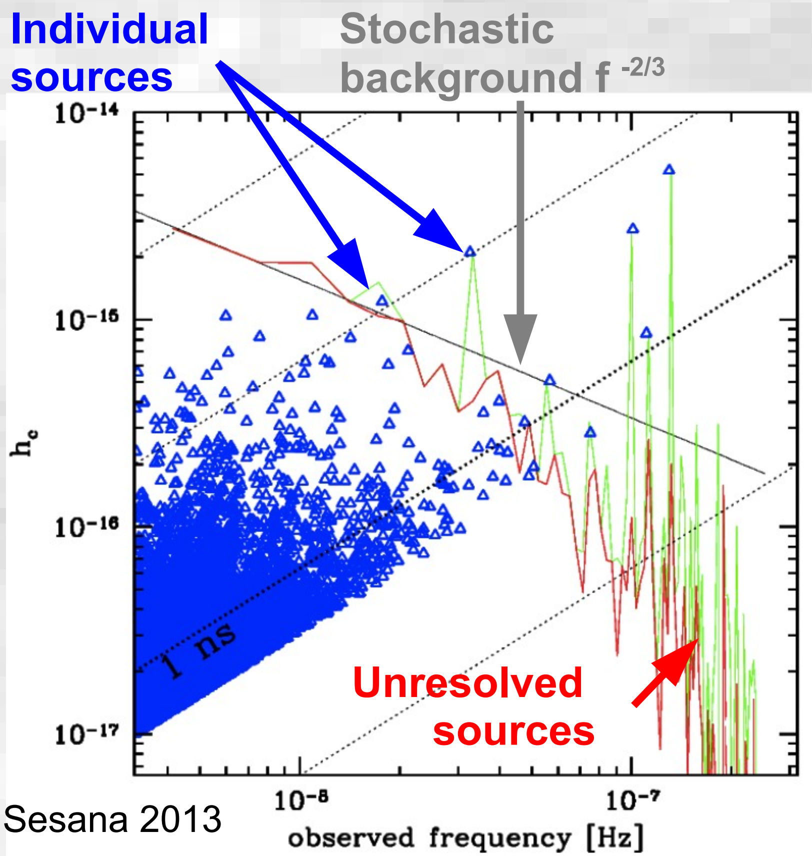
- Fortunately, quadrupole leads to *characteristic periodic residuals* of order **msecs**

Rem : this will highly benefit from SKA1 band 5 (4.6-13.8 GHz)

Why we need SKA instantaneous sensitivity

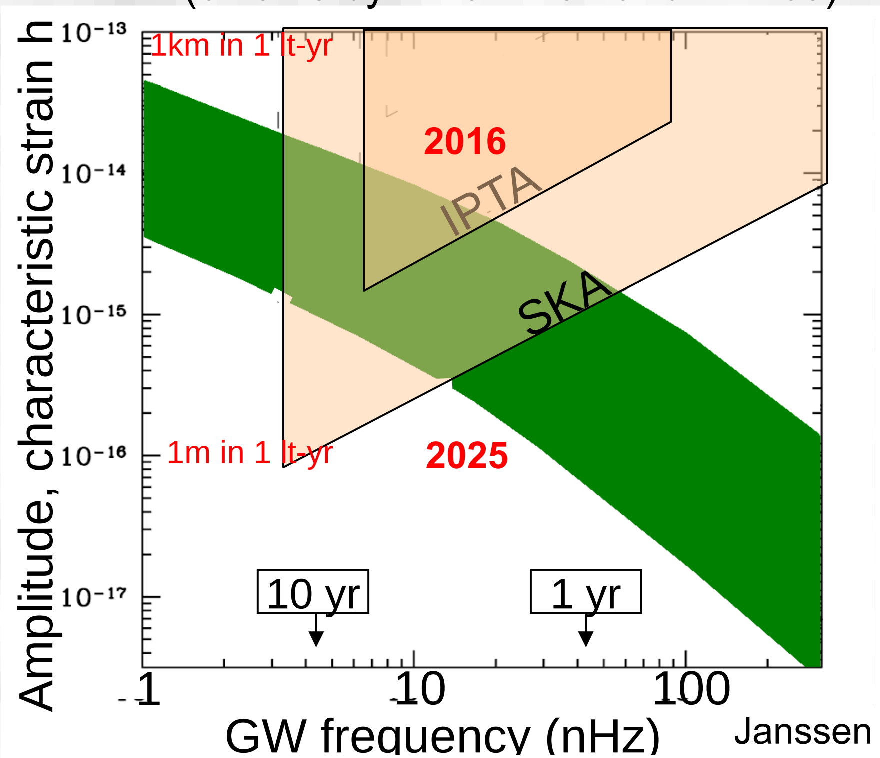
→ get better timing precision on PTA pulsars
→ enlarge the sample of good timers for PTA applications

- Earliest signal expected from binary super-massive black holes in early galaxy evolution (PTA only way to detect $M>10^7 M_\odot$ P_{orb}~10-20 yrs)
- Amplitude depends on merger rate, galaxy evolution and cosmology



Sesana 2013

(cf talks by A.Lommen and D.Nice)

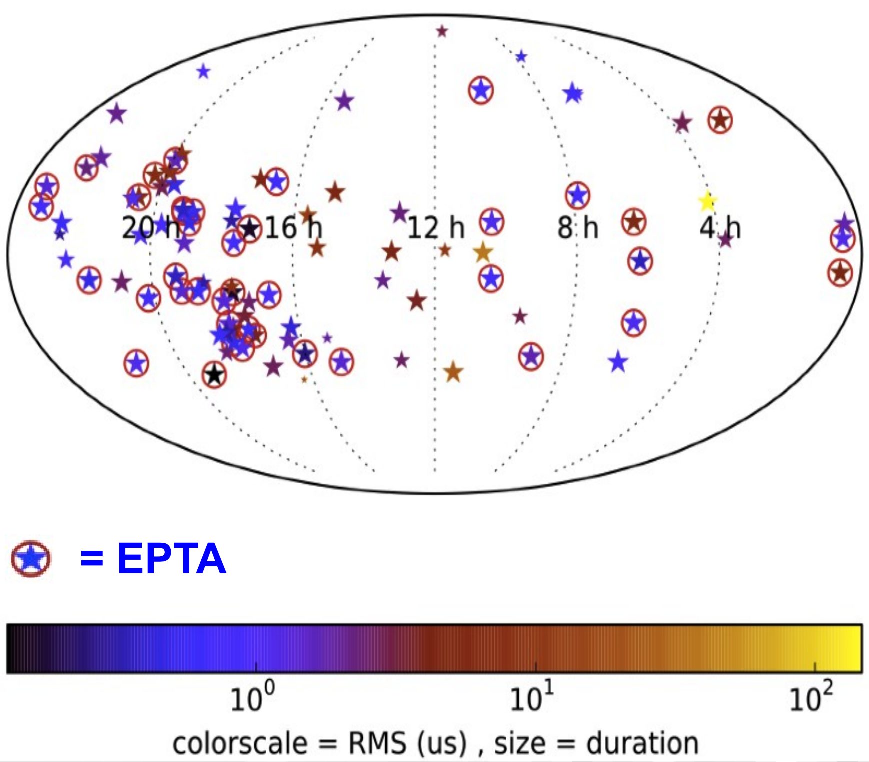


Janssen et al 2015

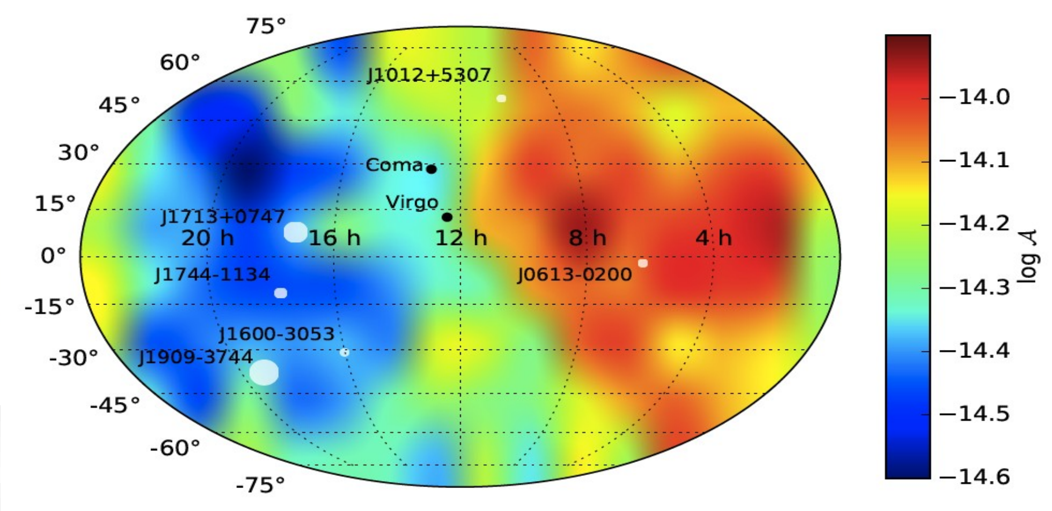
Why we need SKA instantaneous sensitivity

→ get better timing precision on PTA pulsars
→ enlarge the sample of good timers for PTA applications

Distribution of ~40 current best timers above dec -40°
(Petiteau priv. com.)



Single source GW sensitivity map (EPTA)
(Babak et al 2015)

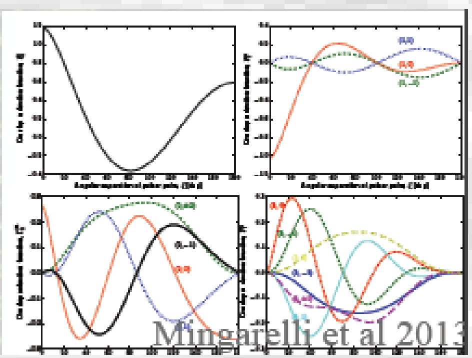


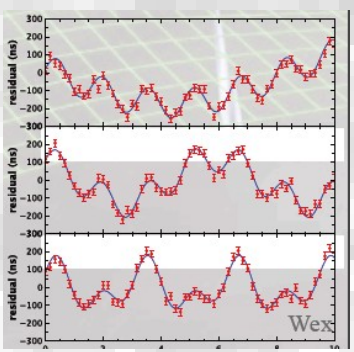
From limit to detection to GW astronomy

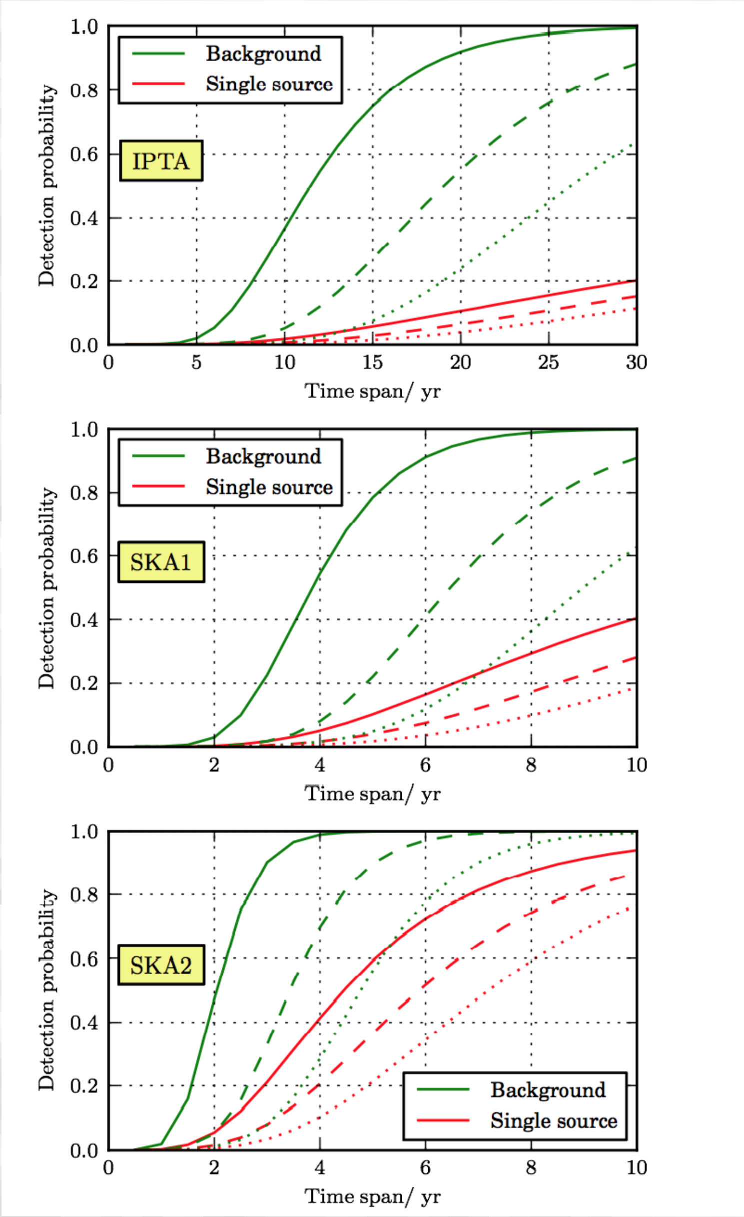
IPTA is getting close to first detection!

SKA1 – Confirmation of the signal
Source identification (characterize spectrum)
Background characterization (anisotropy search)
Source localization

SKA2 – GW astronomy
Constrain/study Galaxy evolution
Characterization of inspiral phase of SMBHBs
Tests of gravity
- Polarization properties
- Mass of graviton







Rosado, Sesana & Gair 2015

Conclusions

With the SKA :

Many tests will improve by continuing timing observations with **better sensitivity**

The combination of SKA-imaging capabilities with e.g. GAIA **astrometric** and E-ELT **photometric/spectrometric data in parallel** to SKA timing will improve NS mass measurements and extrinsic contribution to $\dot{P}_b$

Test Strong Equivalence Principle in various gravity field regimes

Evidence the **dragging of space time by the rotation of a black hole**

Test the no-hair theorem and cosmic censorship with precise measurement of quadrupole of Galactic central black hole

Characterize the SMBHB GW stochastic background at low frequencies and constrain hierarchical galaxy formation models

Study the merger evolution of a SMBHB through both earth and pulsar term